The role of cover crops in irrigated systems: Water balance, nitrate leaching and soil mineral nitrogen accumulation

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ABSTRACT

Using cover crops (CC) in semiarid irrigated areas is often limited by low nutrient and water-use efficiency. This work was conducted over 3.5 years to determine the effect on NO_3^- leaching, water balance and soil mineral N accumulation of replacing fallow with CC in irrigated systems. Treatments studied during the maize (*Zea mays* L.) intercrop period were: barley (*Hordeum vulgare* L.), vetch (*Vicia villosa* L.) and fallow. Soil water content was monitored daily to a depth of 1.3 m and used with the numerical model WAVE to describe the water balance. Determination of crop canopy parameters was based on digital image analysis, and root depth in capacitance sensor readings. Nitrate leaching was calculated multiplying drainage by the soil solution nitrate concentration. Soil mineral N was determined before sowing CC and maize. Over the study, cumulative nitrate leaching in the fallow, vetch, and barley was 346, 245, and 129 kg N-NO_3^- ha^{-1}, respectively; occurring more than 77% during the intercrop period. In dry winters, NO_3^- accumulated in the topsoil, and CC controlled the NO_3^- leaching during the initial maize growth stages. Vetch was less efficient than barley at controlling leaching, but enhanced soil N retention. The CC controlled NO_3^- leaching and recycled N inside the cropping system.

1. Introduction

Irrigated agriculture in semiarid areas contributes to crop productivity and diversification but has considerable potential for the contamination of groundwater because crops are abundantly fertilised to achieve high yield potentials (Vázquez et al., 2006). In particular, maize has long been recognised as a major contributor to nitrate (NO_3^-) pollution from irrigated areas around the world (Díez et al., 1997; Causapé et al., 2004; Klocke et al., 1999; Strock et al., 2004). Adjusting nitrogen (N) and water application to crop requirements is a well-known technique for controlling NO_3^- losses (Gehl et al., 2005). However, maize usually recovers less than 50% of the fertiliser N, and large amounts of residual N are left in the soil at harvest (Bundy and Andraski, 2005; Gabriel and Quemada, 2011). This residual N is prone to leaching during the intercrop period, increasing the NO_3^- loss and decreasing the efficiency of N use at the cropping-system level (Dinnes et al., 2002). The sustainability of these cropping systems depends on developing agricultural techniques that reduce NO_3^- loss and provide a measurable benefit to the environment and the producers.

Replacing intercrop fallow with cover crops (CC) has been reported to increase retention of post-harvest surplus inorganic N, improve efficiency of N use and reduce NO_3^- leaching in humid regions (Hargrove, 1991; McCracken et al., 1994; Thorup-Kristensen et al., 2003). The use of CC in dry regions has often been limited because of unsuccessful stand establishment or low water-use efficiency (Unger and Vigil, 1998). Nevertheless, in irrigated semiarid areas in which cover crop establishment can be assured, consequent soil or nutrient conservation could increase the sustainability of the cropping systems. Recently, Salmerón et al. (2010) have reported that CC in semiarid areas did not affect drainage or NO_3^- leaching during the intercrop period, but the crops did reduce NO_3^- leaching during the early growth stages of the next maize season. By contrast, Sánchez-Martín et al. (2010) have shown the relevance of N losses during the fallow period in irrigated systems in central Spain, particularly NO_3^- leaching losses in wet autumns. More information is needed to clarify the role of CC in controlling NO_3^- leaching in irrigated semiarid areas and to define suitable situations in which cover cropping may help to achieve water quality goals following maize cultivation.

Quantification of NO_3^- leaching below the root zone determines the contribution of agricultural practices to the NO_3^- contamination of groundwater, but leaching is difficult to measure without disturbing the soil (Webster et al., 1993). Various methods have been used to collect water samples from the unsaturated zone: profile soil sampling (Liang et al., 1991; Németh, 1995; Lidon et al., 1999), tile drains (Sogbedji et al., 2000; Strock et al., 2004), drainage from watersheds (Isidoro et al., 2006), pan and wick lysimeters

(Toth and Fox, 1998; Feaga et al., 2010), and monolith lysimeters (Bergstrom and Johansson, 1991; Salmerón et al., 2010). All these methods have advantages and disadvantages, but no single, direct method exists for soil solution sampling under most soil conditions (Gehl et al., 2005; Tuller and Islam, 2005). Indirect methods based on a detailed knowledge of soil water dynamics combined with measuring soil water NO_3^- using ceramic cup samplers allows for the quantification of NO_3^- leaching with minimal soil disturbance and is practical for use in studies with multiple replications and treatments (Normand et al., 1997; Paramasivam et al., 2001; Vázquez et al., 2005). The calculation of drainage or water percolation below the root zone is one of the main factors determining NO_3^- leaching in indirect methods (Arregui and Quemada, 2006). Physically based numerical models for soil water movement can be useful tools to quantify water draining and overall water dynamics (Muñoz-Carpena et al., 2008). However, a large number of parameters are involved in these models, and the success of the predictions strongly depends on the parameter identification and on the model's sensitivity to these parameters (Šimůnek et al., 1999). To overcome this limitation, inverse modelling can be used to identify the basic flow and transport parameters. This procedure has the advantage of results that are based on variables monitored under field conditions (Ritter et al., 2003). The process iteratively searches for the best set of parameters by varying the parameters and comparing the empirically measured response of the system with the numerical solution provided by the model (Šimůnek et al., 1999). The development of multisensor probes has allowed continuous monitoring of soil water content at different depths with minimum soil disturbance (Fares and Alva, 2000), providing data sets over large time scales that can reduce the uncertainties in a model's predictions. In addition, monitoring crop parameters with a large impact on water dynamics, such as root depth or soil cover, may also help to increase our confidence in the results.

The general goal of this study was to evaluate the effect on NO_3^- leaching and soil mineral N accumulation of replacing fallow with a cover crop in an irrigated maize production system. The specific objectives included quantifying the effect on water balance and the total amount of NO_3^- leaching by using a combination of field data and modelling results.

2. Materials and methods

2.1. Experimental setup

The study was conducted over 3.5 years at the La Chimenea Field Station (40°03′N, 03°31′W, 550 m a.s.l.), which is located in the central Tajo river basin near Aranjuez (Madrid, Spain). The soil at the field site is a silty clay loam (Typic Calcixerept; Soil Survey Staff, 2003). It has a basic pH, is rich in organic matter and has low stone content throughout the soil profile (Gabriel and Quemada, 2011). Located in the river terrace the water table is at ~4.5 m depth and the slope close to zero, resulting in negligible runoff. The area has a Mediterranean semiarid climate (Papadakis, 1966) with high interannual variability. The mean annual temperature is 14.2 °C, and the average annual rainfall is 350 mm with less rain in the summer and more in the autumn. Measurements of the temperature, humidity, radiation, PAR (photosynthetically active radiation), rainfall and wind were recorded throughout the experimental period by a field micrologger (CR23X, Campbell Scientific, Logan, UT, USA) (Fig. 1).

Twelve plots (12 m × 12 m) were randomly distributed in four replications of three cover cropping treatments: barley (*Hordeum vulgare* L.), vetch (*Vicia villosa* L.) and fallow. The CC was broadcast by hand over maize stubble and covered with a shallow cultivator in October (05/10/2006, 11/10/2007, 09/10/2008, and 05/10/2009). Because of water restrictions in autumn in this area, CC was established on residual moisture and no irrigation was applied. All the treatments received one application of glyphosate 2% (N-phosphonomethyl glycine) in March (22/03/2007, 24/03/2008, 11/03/2009, and 15/03/2010); three weeks later, the plots were sown with maize (*Zea mays* L.) by direct sowing. The maize was harvested in early autumn (08/10/2007, 2/10/2008 and 29/09/2009), and the residues were removed from the plots. Water was uniformly applied by a sprinkle irrigation system (12 m × 12 m, 9.5 mm h^{-1}) according to the crop evapotranspiration (ETc) requirements calculated by the FAO (the Food and Agriculture Organization of the United Nations) method (Allen et al., 1998). The reference evapotranspiration (ETo) was calculated using the Penman–Monteith model, and the crop coefficient was obtained using the relationship for maize in semiarid conditions (Martínez-Cob, 2008). A flowmeter was installed just before the experiment to measure the amount of water applied. Each plot received 210 kg N ha^{-1} as ammonium nitrate broadcasted by hand and split in two applications: 140 kg N ha^{-1} when maize had 4 leaves and 70 kg N ha^{-1} when it had 8; followed by an irrigation event to enhance infiltration and avoid ammonia volatilisation losses. Before sowing, 120 kg P ha^{-1} and 120 kg K ha^{-1} were applied each year. A more detailed description of the experimental site and design can be found in Gabriel and Quemada (2011).

The soil water content was monitored hourly in this study using the EnviroSCAN® capacitance probe (Sentek Pty Ltd., Stepney, Australia) that has been described in detail by Paltineanu and Starr (1997). Sixty-three capacitance sensors were mounted on nine plastic extrusions (three repetitions per treatment), introduced in nine access pipes and connected to three data loggers. To ensure measurement reliability, a normalisation procedure was conducted that obtained reference readings by exposing each sensor to air and water (~20 °C). The sensors were centred at 10, 30, 50, 70, 90, 110 and 130 cm below the soil surface in each plastic extrusion, and normalised readings were registered every hour. For model comparison, a daily average of the hourly readings from the 0 to 20 (10), 20 to 40 (30), 40 to 80 (60), 80 to 120 (100) and 120 to 140 (130) cm-deep soil layers was used. The average readings were transformed into soil volumetric water content using a calibration equation that was obtained at the experimental site for this specific study (Gabriel et al., 2010). The soil water-content dataset was later used in combination with a numerical model to obtain the water balance.

2.2. Direct estimation of crop parameters

Quantification of the water balance components is very sensitive to evapotranspiration and to the rooting depth (Allen et al., 1998), therefore, both variables were obtained based on actual measurements. The extent of the soil coverage by the CC, measured by digital analysis, was used to monitor leaf area index (LAI). Four pictures were taken with a Nikon S210 Coolpix camera in each of the eight plots with CC every 15 days and were always located in the same location. Each image was recorded from a 1.3 m distance directly above the ground with a tripod and without zoom. The images were saved in 2048 × 1536 pixel resolution, and periodic images of the entire plot were taken to confirm the plot order. The quantification of the plant ground cover from the images was performed using SigmaScan Pro 5® software (Systat software Inc., Chicago, IL, USA) with the macro "Turf analysis" developed by Karcher and Richardson (2005). The LAI was obtained using Mullan and Reynold's (2010) relationship between LAI and the crop ground cover. The plant ground cover was also used for cover crop K_c (dimensionless evapotranspiration crop coefficient) estimation using the FAO method (Allen et al., 1998). The maximum K_c was equal to 1.1 for the barley and 1.0 for the vetch according to the FAO recommendations; the maximum K_c was reached when the crop covered 80% of the

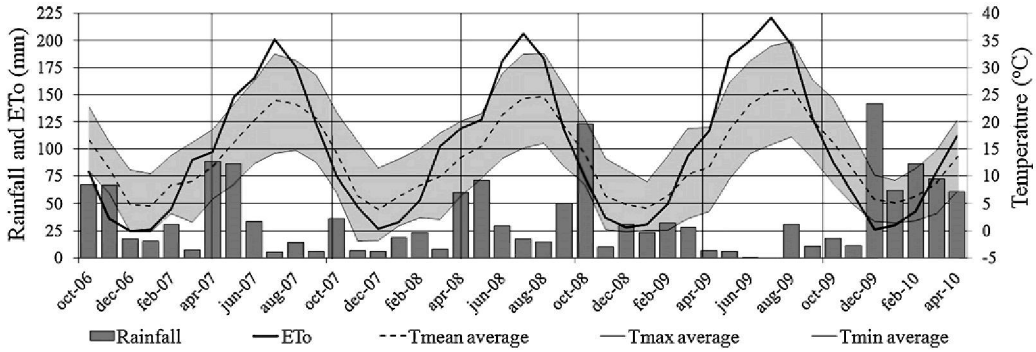

Fig. 1. Monthly rainfall, ETo (modified Penman-Monteith method; Allen et al., 1998), mean temperature, average of maximal temperatures, average of minimal temperatures during the experimental period at Aranjuez (Madrid, Spain).

soil. The maize LAI was obtained by measuring the long, wide and senescence proportions of each leaf in three reference plants per plot (Montgomery, 1911). The maximum maize K_c was equal to 1.2 following the FAO recommendations. The cover crop and maize biomass production and N content were obtained from the same location using the published results by Gabriel and Quemada (2011) elsewhere.

The root depths for the CC and maize were estimated from the hourly EnviroSCAN® sensor data set. When a sensor showed water depletion during the day but not the night (i.e., water lost through transpiration), it was concluded that the roots had reached the sphere of influence of that sensor. Therefore, the sensor depth was considered to be the active root depth. Once a root depth was attained during a growing season, we assumed that the depth was either maintained or increased (based on sensor readings) but never reduced.

2.3. Model description

The mechanistic-deterministic WAVE model (Water and Agrochemicals in soil, crop and Vadose Environment; Vanclooster et al., 1996) was used to describe the water flow in the vadose zone. The model integrates other earlier models: SWATRE (Simulating WATer Root Evapotranspiration; Belmans et al., 1983), SWATNIT (Simulating WATer and NITrogen; Vereecken et al., 1991), the universal crop growth model SUCROS (Simple and Universal CROp growth Simulator; Van Keulen et al., 1982; Spitters et al., 1988) and the LEACHN model (Leaching Estimation and CHemistry model-Nitrogen; Wagenet and Hutson, 1989) subroutines for heat and N transport. It is structured in five modules for water transport, solute transport, heat balance, N transformation and crop growth, but only the water-transportation module was used in this study. The WAVE model allowed finding a numerical solution to the one-dimensional isothermal Darcian flow equation in a variably saturated, rigid, porous medium that was modelled by a Richards equation with water uptake by a root plant sink. The sink was simulated using the universal crop growth component option in the model, using only the crop parameters estimated from direct measurements (LAI, K_c, root depth). To estimate generic crop root characteristics, the maximum root water uptake ($S_{\max}$ [$L^3\,L^{-3}\,T^{-1}$]) was linearly limited by the pressure head effect (Feddes et al., 1978). This limitation is driven by four critical-matrix pressure heads: h_0, h_1, h_2 and h_3 [L]. Between h_1 and h_2, there is no reduction in the water extraction. However, a reduction does occur between h_0–h_1 and h_2–h_3, owing to a lack of oxygen and water stress, respectively. Below h_3, the water extraction ceases owing to drought stress. The atmospheric demand is estimated by dividing the potential crop evapotranspiration into potential transpiration and evaporation. LAI was used as the division parameter for this splitting (Vanclooster et al., 1996).

The water-retention model was the curve described by van Genutchen (1980), which depends on the soil water content [$L^3\,L^{-3}$] at the matrix pressure head, the saturated and residual soil water content (θ_s and θ_r, respectively) [$L^3\,L^{-3}$], the inverse of the air-entry value (α) [L^{-1}] and two curve shape parameters (n and m, where m is assumed to be equal to $1-1/n$). The unsaturated hydraulic conductivity function has been described by Mualem (1976) and depends on the saturated hydraulic conductivity (K_s) [LT^{-1}], the effective saturation and the pore connectivity parameter for the tortuosity and correlation between pore sizes.

The model inputs and outputs were determined on a daily basis, and the soil compartments (soil layers subdivisions) were 5 cm in depth. These compartments are used by the model to define nodes in the middle of each compartment and to solve the Richards equation by finite difference techniques (Celia et al., 1990) with space implicit and time explicit. The simulated soil was 140 cm deep with free drainage as the bottom boundary condition and five layers (0–20, 20–40, 40–80, 80–120 and 120–140 cm). However, the drainage was estimated at a 120 cm depth before the calcic layer.

2.4. Indirect parameter estimation: sensitivity analysis and inverse calibration

The WAVE model requires a large number of input parameters, and not all of them are easily measurable or have large spatial variability. Therefore, an inverse calibration and an optimisation of the hydraulic parameters were performed with only one part of the available data set, leaving the rest for model validation. First, the calibration of the soil hydraulic parameters was conducted with data from the fallow treatment to avoid interaction with crop parameter determination. To explore a large range of soil water conditions, the selected calibration period was from October 2006 to March 2007. In this case, the van Genuchten-Mualem hydraulic and curve-shape parameters θ_s ($m^3\,m^{-3}$), θ_r ($m^3\,m^{-3}$), α (cm^{-1}), n and K_s (m day^{-1}) (van Genutchen, 1980; Mualem, 1976) were selected for inverse optimisation of the five layers. The range of each value was defined as a normal distribution except for K_s, which usually follows a lognormal distribution with a mean and typical deviation measured in the field. The θ_s distribution was obtained as the porosity measured in ten 100 cm^3 soil cores for each layer studied. The θ_r distribution was obtained from the lower water content observed in each EnviroSCAN® sensor and depth. The α and n were obtained from the adjustment of the soil water content data observed at saturation, field capacity and wilting point. The K_s distribution was obtained from ten soil cores for each layer depth using a laboratory constant head permeameter (Klute and Dirksen, 1986). Following the distributions defined for the 25 parameters, 100,000 sets of values were randomly selected to determine the best fit with the observed soil water data at depths of 10, 30, 60, 100 and 130 cm. The fit of the simulations to the observed data was evaluated by the coefficient of efficiency (Ceff) (Nash and Sutcliffe, 1970) and the root mean squared error (RMSE). It was necessary to identify the parameters to which the model was most sensitive to use the model to perform studies on a larger scale. The Morris modified method (Morris, 1991; Saltelli et al., 2005) was used to determine the most influential parameters under these conditions. The less influential parameters were fixed with the values obtained in the better-fitting 100,000 simulations that had been previously performed. Next, 100,000 new data sets (only for the most influential parameters) were used to repeat the simulation and search for the new best fit. The best-fitting hydraulic soil parameters were used for the rest of the period in question.

Next, the root crops' parameters were inverse calibrated. The selected calibration period was from October 2006 to March 2007 for the CC and April to September 2007 for the maize. The calibrated parameters for the barley, vetch and maize were as follows: (i) date when roots reached their maximum inactivity, (ii) pressure head value below which the roots started to extract water from the soil (cm), (iii) pressure head value below which the roots started to extract water optimally from the soil (cm), (iv) pressure head value below which the roots no longer extracted water optimally at a high and low evaporative demand (cm), (v) pressure head value at which the water uptake by the roots ceased (wilting point) (cm) and (vi) maximal root water uptake for each compartment (S_{max}).

The dates when the roots reached their maximum inactivity were only considered for the barley and vetch (which were killed with glyphosate); for the maize, this date was the same as the harvest date. The 100,000 data sets were randomly selected following a normal distribution from the recommended range (Vanclooster et al., 1996). For each crop, 100,000 simulations were run, and the best-fitting data set with the observed soil water data at 10, 30, 60, 100 and 130 cm depth was selected.

2.5. *WAVE model validation and application: water balance*

The inverse-calibrated WAVE model was validated using two maize periods (April 16th to October 8th, 2008 and April 3rd to October 4th, 2009) and three fallow and cover crop periods (October 11th, 2007 to April 15th, 2008, October 9th, 2008 to April 2nd, 2009 and October 5th, 2009 to April 16th, 2010). The goodness of fit was evaluated using the same method as in the calibration, based on the Ceff and RMSE of the simulated and observed soil water content. Once the WAVE model was calibrated and validated for the soil and crops, it was applied to the three replications for each treatment over the entire period in question. Information about the water balance components (evaporation, transpiration, drainage, and runoff) was obtained from the model output and averaged for each treatment.

2.6. *Nitrate leaching and soil N_{min}*

Samples of the soil solution at 120 cm were taken every 15 days or after 20 mm of rain using 36 ceramic suction cups (Lord and Shepherd, 1993) and a hand-operated vacuum pump connected to a capillary tube and then transferred to a storage bottle. The cups were installed at least 1.5 m from the nearest cup, EnviroSCAN® capacitance probe, soil sampling point or plot edge. The ceramic cups (which had a 3.2 cm external diameter and were7.5 cm in length) had maximum pore sizes of 1 μm and were attached to a flexible nylon capillary tube that was long enough to protrude above the soil surface and was sealed at the end by a clamp. The installation consisted of a vertical hole that was slightly larger than the cup diameter and 122–124 cm deep. The excavated topsoil, upper soil and lower subsoil were kept separate. Before the porous cups were gently lowered to the bottoms of the holes, thick slurry

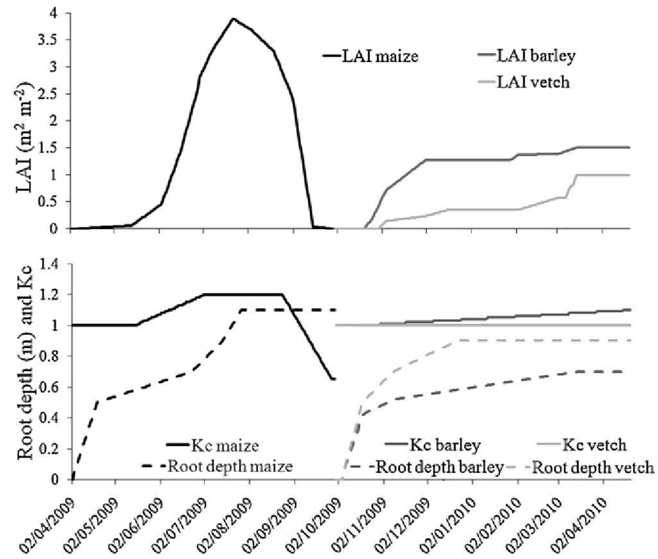

Fig. 2. The evapotranspiration crop coefficient (K_c), LAI and root depth for an entire maize/cover-crop cycle (maize in 2009 and cover crop in 2009/10).

prepared from the lower subsoil was poured into the holes. The soil was repacked and consolidated, and a 10 cm layer of dry bentonite was added at a 20-cm depth to act as a watertight plug and avoid preferential water flow. The surface soil was then repacked up to the ground level with the topsoil. Using suction, these cups were maintained at close to 333 cm (the field capacity) during the entire experimental period.

The soil solution was stored in a freezer for later analysis. The nitrate concentration in the soil solution was determined by spectrophotometry after reduction with a cadmium column (Keeney and Nelson, 1982), and ammonium was measured using the method of Solorzano (1969). The mean NO_3^- and ammonium concentration was calculated using samples from the ceramic cups for each sampling date and treatment. The nitrate leached over the soil solution sampling intervals was calculated as the product of mean NO_3^- concentration of the soil solution and the daily drainage obtained for the sampling interval using the WAVE model. When in a treatment, the soil solution was collected in less than 50% of the ceramic cups the drainage was considered zero and was compared with the WAVE drainage estimation. The quantity of nitrate that leached over the soil solution sampling intervals was determined to obtain the cumulative mineral N leaching to below 1.2 m.

Before each sowing of the CC and maize, four 0- to 1.2-m depth holes were dug in each plot using an Eijkelkamp® (Giesbeek, The Netherlands) helicoidal auger to determine soil mineral N (N_{min}). The samples were taken from 6 depths, mixing the soil obtained from the four holes every 0.20 m. Each soil sample was placed in a firmly closed plastic box, immediately transported and refrigerated (4–6 °C). Within three days, a 1 M KCl extraction was performed, and the extract was frozen. Later, the soil extracts were analysed for N-NH_4^+ and N-NO_3^- according to the methods of Solorzano (1969) and Keeney and Nelson (1982), respectively.

3. Results

3.1. *Direct estimation of crop parameters*

The LAI evolution was similar during the three maize periods, reaching a maximum of 3.89 m^2 m^{-2} in the last week of July (from 22nd to 29th July) with no significant differences between the treatments (Fig. 2). During the cover crop growing season, the LAI evolution depended on the treatment and year. The maximum

LAI reached by the barley was 1.75 m^2 m^{-2} during the first three periods but only 1.5 m^2 m^{-2} for 2009/10. The vetch only reached LAIs of 1.75 m^2 m^{-2} in 2006/07 and 1.66, 1.10 and 0.99 m^2 m^{-2} in 2007/08, 2008/09 and 2009/10, respectively. The LAI evolution during autumn was faster for barley than for the vetch treatment in two years and was similar in 2006 and 2008. Fig. 2 shows the results for 2009–2010; similar patterns were observed in the other years, although the cover crop values varied depending on annual climatological conditions.

During the three maize periods, the root activity depth based on the soil moisture sensors observations varied from 90 cm to 130 cm with no significant differences between the treatments. During the cover crop periods, the root depth varied between the years but not between treatments except in 2009/10, when the vetch roots extracted water from deeper layers than did those of the barley (Fig. 2). The cover-crop roots reached depths varying from 70 cm to 100 cm during 2006/07, 2008/09, and 2009/10. In 2007/08, when the soil was extremely dry owing to limited precipitation, the roots were able to actively reach a depth of only 50 cm in both cover crop treatments.

3.2. *Indirect parameter estimation*

The model calibration during the first fallow period was performed within the parameter probabilistic distribution range observed in the field (Table 1). The sensitivity analysis after the first 100,000 simulations showed that n in all five depths, θ_r in the 40–80 and 80–120 cm depths and K_s in the 0–20 and 20–40 cm depths were the most influential parameters in the models for these conditions. The second optimisation performed for these nine parameters within the observed ranges showed the observed and simulated soil water content at five monitoring depths at the end of the calibration (Figs. 3 and 4). This last optimisation was performed by fixing the other sixteen parameters to values calibrated in the best-fitting first 100,000 simulations (Table 1). A good match between the predicted and simulated values was observed by visual inspection. The simulated values fell within the maximum and minimum observed water contents from the different sensors for each depth (Fig. 3). The visual inspection was supported by the statistical fit criteria. The predicted water content for the entire profile had a Ceff of 0.896 and an RMSE of 6.8 mm. However, volumetric water content analysed by layer had a Ceff of 0.913 and an RMSE of 0.007 m^3 m^{-3}.

The inverse calibration during the first cover crop period was optimal when roots reached their maximum inactivity 7 d after glyphosate application for vetch and after 6 d for barley. The rest of root and plant parameters calibrated and their optimised value are shown in Table 2. The observed and simulated soil water contents for the cover crop treatments were similar for the five monitoring depths (Fig. 4). The predicted water content for the entire profile of the vetch treatment had a Ceff of 0.841 and an RMSE of 10.9 mm, and the barley treatment had a Ceff of 0.905 and an RMSE of 9 mm. However, volumetric water content analysed by layer had a Ceff of 0.844 and an RMSE of 0.009 m^3 m^{-3} for the vetch treatment and a Ceff of 0.930 and an RMSE of 0.006 m^3 m^{-3} for the barley (Table 3).

The model calibration during the first maize period was optimal for the data set in Table 2, which was obtained from the probabilistic distributions observed in the field and from the literature. The observed and simulated soil water contents for the maize were similar for the five monitoring depths (Fig. 4). Considering all the maize treatments together, the predicted water contents for the entire profile had a Ceff of 0.860 and an RMSE of 9.5 mm. However, volumetric water content analysed by layer had a Ceff of 0.859 and an RMSE of 0.008 m^3 m^{-3} (Table 3).

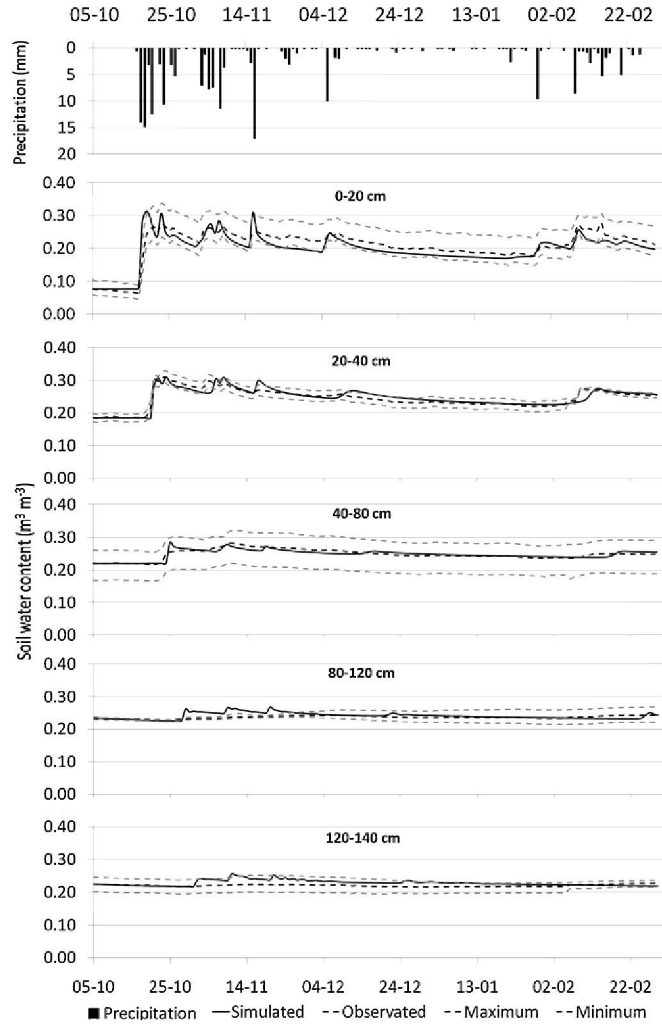

Fig. 3. The soil water content simulated using the WAVE model versus the maximum, minimum and average water content observed using the capacitance sensors in the fallow plots at different depths during the calibration period (2006/07).

3.3. *WAVE validation and application: water balance*

The validation of the model using the soil water content data from the remainder of the experimental period was similar to that of the calibration period (Fig. 4 and Table 3). During the three cover-crop periods of 2007/08, 2008/09 and 2009/10, the predicted water content for the entire profile had a Ceff of 0.828 for the vetch treatment, a Ceff of 0.844 for the barley, and a Ceff of 0.846 for fallow. However, volumetric water content analysed by layer had Ceff of 0.824 for the vetch, 0.876 for the barley and 0.804 for the fallow. During the two maize periods, 2008 and 2009, the predicted water content for the soil profile had a Ceff of 0.860 for the three treatments together and of 0.862 for the volumetric water content analysed by layer. After heavy rain or irrigation events, the WAVE model produced larger increments in the soil water content from the upper layers than were observed using the EnviroSCAN® probes, owing to the daily time step. These outlier points are visible in Figs. 3 and 4, but they were corrected by the model on next day, which reduced their effect on Ceff and RMSE.

The daily outputs from the model applications were used to obtain seasonal values for evaporation, transpiration, runoff, and drainage for all the experimental treatments (Table 4). The runoff was equal to 4 mm for all the periods and was concentrated during the maize growth with no significant differences between the treatments. There were no differences between the treatments in

Table 1
The initially observed ranges (mean and standard deviation) and the optimised values of soil hydraulic parameters for the WAVE model.

Depth (cm)	θ_r [a] ($cm^3\ cm^{-3}$)		θ_s [b] ($cm^3\ cm^{-3}$)		α [c] (cm^{-1})		n [c]		K_s [d] ($cm\ day^{-1}$)	
	Model	Observed	Model	Observed	Model	Observed	Model	Observed	Model	Observed
0–20	0.060	0.050 ± 0.015	0.499	0.459 ± 0.036	1.243	1.28 ± 0.31	1.441	1.37 ± 0.17	1009	695 ± 79.2
20–40	0.070	0.092 ± 0.039	0.420	0.432 ± 0.029	1.150	1.25 ± 0.32	1.283	1.33 ± 0.18	510	272 ± 34.2
40–80	0.105	0.092 ± 0.041	0.330	0.456 ± 0.024	1.480	1.67 ± 0.33	1.172	1.25 ± 0.15	979	1349 ± 185.4
80–120	0.128	0.112 ± 0.041	0.305	0.451 ± 0.027	3.400	3.04 ± 1.12	1.190	1.26 ± 0.17	525	167 ± 18.0
120–140	0.100	0.105 ± 0.053	0.298	–	2.381	–	1.174	–	1001	–

[a] θ_r: residual water content.
[b] θ_s: saturation water content.
[c] α: inverse of the air entry value, and n: curve shape parameter of the water retention model described by van Genutchen (1980).
[d] K_s: saturated hydraulic conductivity.

Table 2
The initially observed ranges (mean and standard deviation) and the results of the optimised crop root parameters for the WAVE model.

	h_0 [a]	h_1	h_2	h_3	S_{max}				
	(cm)	(cm)	(cm)	(cm)	0–20 ($m^3\ m^{-3}\ day^{-1}$)	20–40 ($m^3\ m^{-3}\ day^{-1}$)	40–80 ($m^3\ m^{-3}\ day^{-1}$)	80–120 ($m^3\ m^{-3}\ day^{-1}$)	120–140 ($m^3\ m^{-3}\ day^{-1}$)
Vetch	−1	−29	−305	−16,797	0.010	0.005	0.004	0.003	0.003
Barley	−5	−31	−511	−18,296	0.009	0.007	0.004	0.003	0.003
Maize	0	−11	−496	−17,954	0.011	0.003	0.003	0.003	0.003
Range	−20 ± 10	−100 ± 50	-500 ± 100	$-1.6E^4 \pm 1E^3$	$9E^{-3} \pm 2E^{-3}$	$6E^{-3} \pm 2E^{-3}$	$5E^{-3} \pm 2E^{-3}$	$4E^{-3} \pm 2E^{-3}$	$4E^{-3} \pm 2E^{-3}$

[a] Critical-matrix pressure heads (h_0, h_1, h_2 and h_3) that limit the maximum root water uptake (S_{max}) in the WAVE model (Vanclooster et al., 1996).

Table 3
The fit analysis for the WAVE-simulated and measured water contents for the entire soil profile and individual layers during the first calibration and next validation periods.

	Soil profile water content				Individual layers water content			
	Calibration period		Validation period		Calibration period		Validation period	
	Ceff [a] (mm)	RMSE (mm)	Ceff (mm)	RMSE (mm)	Ceff ($m^3\ m^{-3}$)	RMSE ($m^3\ m^{-3}$)	Ceff ($m^3\ m^{-3}$)	RMSE ($m^3\ m^{-3}$)
Fallow	0.896	6.8	0.846	8.6	0.913	0.005	0.804	0.007
Vetch	0.841	10.9	0.828	11.2	0.844	0.009	0.824	0.009
Barley	0.905	9.0	0.844	10.1	0.930	0.006	0.876	0.008
Maize	0.860	9.5	0.799	7.1	0.859	0.008	0.862	0.006

[a] Coefficient of efficiency (Ceff) and root mean squared error (RMSE).

Table 4
Water balance (precipitation, irrigation, evaporation, transpiration and drainage) and nitrate leaching for the three treatments, with three repetitions over the 3.5 years of the study.

Period	Treatment	Precipitation [a] (mm)	Irrigation [a] (mm)	Evaporation [a] (mm)	Transpiration [a] (mm)	Drainage [a] (mm)	Leaching [a] ($kg\ N\ ha^{-1}$)
		Cover crop growing season					
2006/07	Fallow	250	–	84 [b] a	0 c	105.6 a	86.4 a
	Vetch	250	–	63 b	108 b	60.3 b	35.2 b
	Barley	250	–	64 b	117 a	47.4 c	36.0 b
2007/08	Fallow	101	–	51 a	0 c	0.0 a	0.0 a
	Vetch	101	–	35 b	31 b	0.0 a	0.0 a
	Barley	101	–	31 b	63 a	0.0 a	0.0 a
2008/09	Fallow	246	–	67 a	0 b	131.7 a	45.1 a
	Vetch	246	–	59 b	38 a	64.0 b	21.9 b
	Barley	246	–	62 b	41 a	62.1 b	12.6 c
2009/10	Fallow	453	–	101 a	0 c	314.7 a	147.3 a
	Vetch	453	–	79 b	42 b	301.3 b	132.4 a
	Barley	453	–	60 c	109 a	233.7 c	54.4 b
		Maize growing season					
2007	Fallow	225	524	93 a	496 a	74.6 a	42.2 a
	Vetch	225	524	93 a	496 a	57.1 b	29.5 b
	Barley	225	524	93 a	496 a	46.8 b	12.3 c
2008	Fallow	207	517	108 a	559 a	21.7 a	3.0 ab
	Vetch	207	517	108 a	560 a	31.0 a	6.3 a
	Barley	207	517	108 a	561 a	0.0 b	0.0 b
2009	Fallow	54	633	123 a	558 a	49.5 a	22.3 a
	Vetch	54	633	123 a	559 a	35.3 a	20.0 a
	Barley	54	633	123 a	559 a	39.0 a	13.5 a

[a] Precipitation and irrigation were measured in the field experiment; evaporation, transpiration and drainage were obtained by modelling the water balance with WAVE (Vanclooster et al., 1996); nitrate leaching was calculated as the product of simulated drainage and the nitrate concentration measured on soil solution from suction cups.
[b] Within year, treatments followed by different letters are significantly different at $\alpha < 0.05$ by Duncan's test.

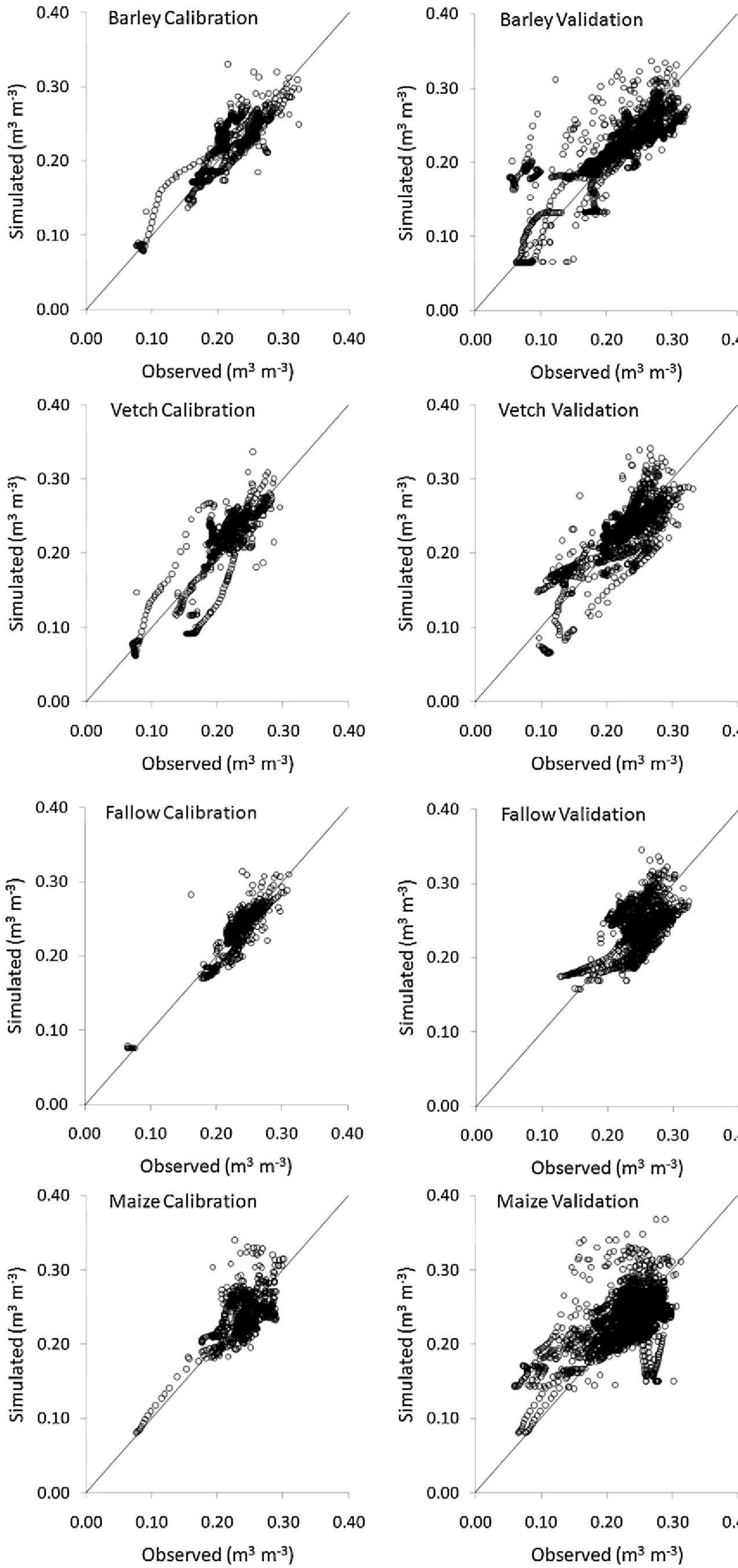

Fig. 4. The soil water content simulated using the WAVE model compared with that observed using the capacitance sensors in the fallow, vetch, barley and maize plots at five depths during the calibration and validation periods.

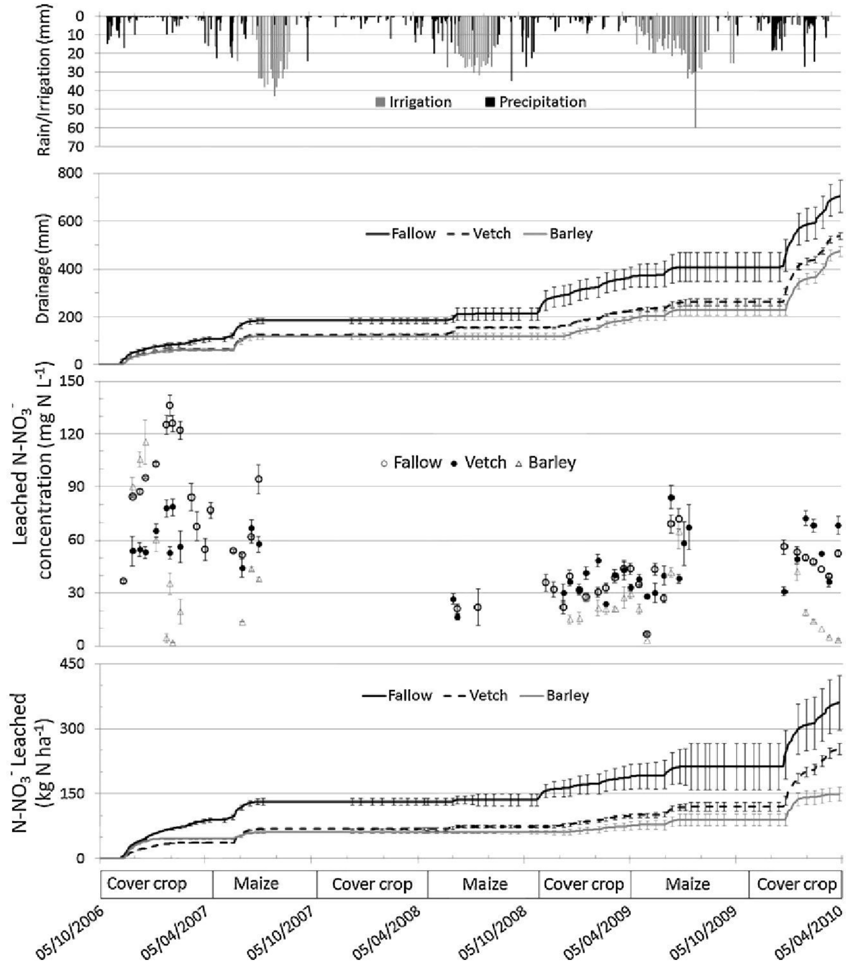

Fig. 5. The water balance simulated using the WAVE model and the N-NO_3^- leaching from the suction cups for the fallow, vetch and barley treatments.

the evapotranspiration during the maize periods (ranging from 589 to 682 mm, depending on the year), but there were differences during the cover-crop period. Each year, the fallow treatment produced larger evaporation than did the other treatments; it ranged from 51 to 101 mm, depending on the year. The largest evapotranspiration corresponded to the barley treatment (from 36 to 97 mm higher than for the fallow), followed by vetch (from 15 to 87 mm higher than for the fallow). The differences between CC were particularly relevant in 2007/08 and 2009/10, when a faster LAI evolution for the barley during autumn led to double the transpiration of the vetch.

Differences in drainage appeared both during the both cover-crop period and the maize period. In 2007, the water storage of the soil profile before planting the maize was lower for the cover-crop treatments, as was the drainage. In 2008, this difference only appeared for the barley, when the depletion of soil water before planting the maize was the larger evapotranspiration during the growing period. The cover-crop period was characterised by a large variability in drainage, ranging from no water percolation below 1.2 m in 2007/08 to more than 230 mm in 2009/10. The drainage occurring during the cover-crop period was always larger for the fallow than for the cover-crop treatments and was larger for the vetch than for the barley, when transpiration was larger in the cereal. The reduction in the total amount of water drained for the CC was due both to a decrease in the water moving down the soil profile after a rain event and to shorter drainage periods. The drainage began later and finished earlier in the cover-crop treatments than in the fallow (Fig. 5).

3.4. Nitrate leaching and N_{min}

The drainage periods calculated using the suction cup observations were well correlated with the WAVE model simulation. The suction cups worked satisfactorily and maintained the suction capacity over the 15 day periods, only losing vacuum during the long period of extremely dry soil in the autumn of 2007/08 and recovering their capacity when the soil became wet again. The soil solution was collected in at least 50% of the cups when the model indicated drainage and in less than 50% of the cups when the model indicated only residual water movement or no drainage. The barley treatment reduced the length of the drainage periods relative to the fallow treatment, with vetch exhibiting intermediate values (Fig. 5).

The NO_3^- concentration observed in the suction cups varied over the experiment but showed some differences. The concentration over the study (~30 mg N-NO_3^- l^{-1}) was more stable in the barley than in the other treatments and was also lower. In the first part of the study only, the barley treatment drainage concentration was higher than 70 mg N-NO_3^- l^{-1}. The average concentration was 57 mg N-NO_3^- l^{-1} for the vetch and 44 mg N-NO_3^- l^{-1} for the fallow treatment with values varying from 20 mg N-NO_3^- l^{-1} to 140 mg N-NO_3^- l^{-1} over the study period. The NH_4^+ concentration was measured, but it was negligible in all the treatments, ranging from 0.0003 to 0.77 mg N-NH_4^+ l^{-1}.

The total NO_3^- leached was obtained by combining the drainage estimated by the WAVE model and the concentration measured by the suction cups (Fig. 5). The fallow treatment leached

Table 5
The residual N_{min} (kg N ha^{-1}) in the upper part of the soil profile (0–80 cm), the bottom part (80–120 cm) and the entire profile (0–120 cm) after the cover crops and maize harvest.

Treatment	After cover crops				After maize harvest		
	2006/07	2007/08	2008/09	2009/10	2007	2008	2009
Vetch 0–40 cm	4.8 b	47.7 a	53.0 a	90.5 a	73.8 a	64.8 a	107.9 a
Barley 0–40 cm	5.7 b	31.6 a	19.0 b	44.0 b	77.4 a	41.4 a	47.8 b
Fallow 0–40 cm	23.9 a	51.0 a	49.8 a	20.7 c	42.2 a	42.3 a	74.7 b
Vetch 0–80 cm	31.2 ab	79.8 a	112.7 a	98.8 a	111.5 a	92.1 a	188.8 a
Barley 0–80 cm	7.1 b	43.3 a	24.5 b	46.5 b	108.9 a	58.9 a	69.1 b
Fallow 0–80 cm	70.3 a	74.9 a	93.2 a	29.1 b	84.9 a	66.9 a	113.7 b
Vetch 80–120 cm	63.6 ab	57.9 a	71.4 a	13.7 a	57.7 a	48.7 a	64.0 a
Barley 80–120 cm	23.5 b	35.3 a	20.6 a	2.40 b	36.8 a	36.6 a	29.8 a
Fallow 80–120 cm	85.86 a	60.9 a	65.1 a	14.1 a	63.6 a	52.4 a	55.8 a
Vetch 0–120 cm	94.8 ab	137.7 a	184.1 a	112.5 a	169.2 a	140.8 a	252.7 a
Barley 0–120 cm	30.6 b	78.6 a	45.1 b	48.9 b	145.6 a	95.6 a	98.9 b
Fallow 0–120 cm	156.1 a	135.7 a	158.2 ab	43.2 b	148.6 a	119.3 a	169.5 ab

[a]Within measuring date and depth, treatments followed by different letters are significantly different at $\alpha < 0.05$ by Duncan's test.

346 kg N-NO_3^- ha^{-1} over the course of the study, whereas the barley treatment leached only 129 kg N-NO_3^- ha^{-1}. The vetch treatment leached an intermediate amount, 245 kg N-NO_3^- ha^{-1}, that was closer to that of the fallow. The differences in NO_3^- leaching during the maize period appeared only in the spring, which was consistent with the drainage reduction, and were statistically significant in 2007. The leaching during the intermaize period represented 81% of the total NO_3^- leached during the study for the fallow treatment, 80% for the vetch and 77% for the barley. The cover-crop period was characterised by large variability in the NO_3^- leaching, which ranged from zero in 2007/08 to 147 kg N ha^{-1} for the fallow treatment in 2009/10. In this last period, the barley reduced NO_3^- leaching by almost 100 kg N ha^{-1} relative to the control. When the drainage was greater for the fallow, the NO_3^- leaching was also greater than for the other treatments (Table 4).

After the four cover-crops period, the vetch treatment contained more soil N_{min} than did the barley and fallow treatments (Table 5). In the first cover-crop growing period, all of the treatments reduced N_{min}. The barley had the largest decrease, followed by the vetch. After the first maize crop maize in 2007, however, no differences in N_{min} content were observed, and this trend continued until the 2008/09 cover-crop growing period. In the barley treatment, the N_{min} accumulation in the soil was smaller after the cover crop with differences in the upper layers relative to the fallow and vetch. After the 2009 maize period, the vetch treatment had a larger N_{min} content, with differences from those of the barley and fallow in the upper 80 cm. At this time, the barley had the smallest amount of N_{min} of the three treatments. During the 2009/10 cover-crop season, a large reduction in N_{min} related to the abundant rainfall and leaching was observed for all the treatments (Fig. 5). The reduction in N_{min} was larger in the vetch and fallow (130 kg N ha^{-1}) than in the barley treatment (50 kg N ha^{-1}). The N_{min} distribution over the soil profile showed that there was N_{min} movement from the upper layers to the bottom and leaching in the lower layers during the cover-crop growing season. A larger depletion of the upper layers occurred with the fallow treatment. By the end of the experimental period, the soil N_{min} content throughout the profile was similar for the barley and fallow treatments. Although most of the N_{min} remained in the upper layers for the CC, it was leached down for the fallow. In the vetch treatment, the N_{min} in the soil profile was more than doubled.

4. Discussion

The differences in the LAI, ground cover and root depth of the crops between the years were attributed to the large variability in the climatic conditions during the growing season, consistent with the differences in biomass production and N content that have previously been reported for this experiment (Gabriel and Quemada, 2011). In Mediterranean and semiarid regions, the use of CC is often limited because they compete with the cash crop for nutrient resources and are thought to decrease the water-use efficiency (Mitchell et al., 1999; Salmerón et al., 2010). In this case, however, replacing fallow with barley did not diminish the LAI or root depth of the maize crop. Competition with the cash crop was pre-emptively mitigated by killing the CC before planting the maize (after about four weeks) and applying a small amount of irrigation water to ensure maize establishment. The barley covered the ground faster than the vetch and showed a larger capability to act as a cover crop. A rapid LAI development in early autumn was linked to an increase in K_c and evapotranspiration from the CC relative to the fallow. The active root depth was uniform over the years for the maize and CC, and only in the unusually dry autumn was the root development limited. These results are consistent with those of Muñoz-Carpena et al. (2008), who showed the large sensitivity of evapotranspiration to LAI and K_c in the WAVE model. Efforts to directly determine these parameters will increase confidence in the model results and are worthwhile when the goal is quantifying the water balance of a plant-soil system.

The use of daily soil water content measurements for an inverse calibration of the hydraulic parameters of a physically based numerical model yielded a good estimation of the soil water processes. The inverse calibration allowed calculating the root-water uptake parameters, which are necessary for the WAVE model and difficult to obtain using any other procedure (Hupet et al., 2003). All of the treatments fit the model to the observed data equally well, as has been previously reported (Muñoz-Carpena et al., 2008; Payet et al., 2009) with Ceff values from 0.846 to 0.918 and RMSE values from 0.006 to 0.009 m^3 m^{-3} for the calibration and verification periods. The RMSE obtained for the soil water sensors in a calibration and validation study at the same experimental site ranged from 0.019 to 0.050 m^3 m^{-3} (Gabriel et al., 2010); therefore, the error in the simulated soil water content values was smaller than the error associated with the measurements. The hydraulic parameters obtained from the inverse calibration were within the variation bound of the measured data, and the crop parameters were consistent with the data provided in the WAVE manual (Vanclooster et al., 1996). Other authors have shown that the most influential hydraulic soil parameters in their experiments were the van Genuchten n and α, as in Mallants et al. (1996), and the n and θ_s, as in Muñoz-Carpena et al. (2008). In our experiment, the van Genuchten n was the most sensitive parameter at all the depths, but the sensitivity of the model to α and θ_s were less relevant. The depth θ_r and shallow K_s were more important under these conditions. The WAVE model was a useful tool for the different situations presented. The Richards equation application for the soil water movement calibrated with the observed data improved the accuracy of the water balance solution in all of the layers and over the entire profile throughout the study period.

The WAVE model was able to reflect the differences in evaporation and transpiration between the treatments and climatic conditions according to the crop development. The CC reduced evaporation and increased transpiration, leading to a larger evapotranspiration than for the fallow. This water extraction capability allowed the cover crop treatments to reduce the amount of water in the soil and drainage. Barley showed better potential as a cover crop than did vetch in 2006/07 and 2009/10, when a larger evapotranspiration and a lower drainage was predicted. The maize crop periods had high evapotranspiration because of the large amount of biomass produced, but they had low drainage because the water irrigation was adjusted to the crop requirements. All the treatments received the same amount of water as irrigation or precipitation, with the evapotranspiration being the most important difference between the treatments and the precipitation the most important difference between the years. The drainage during the maize periods (21, 22 and 20% of the total drainage in the fallow, vetch and barley treatments, respectively) only occurred in the spring, the rainy season, and the maize still did not develop a large biomass. The differences in drainage between the treatments during the maize period (in 2007 and 2008) were derived from the differences in the soil water content at the maize planting and linked to water depletion by the CC. During the cover crop periods, the drainage varied greatly between study years, according to the precipitation. The differences between treatments were larger. While the cumulative drainage during the intercrop periods was 552 mm for the fallow, it was 426 for the vetch and 343 for barley. This reduction was the result of soil water depletion by the CC, which reduced the water content in the soil profile and the length of the drainage periods. The drainage began later and finished earlier for the cover-crop treatments than for the fallow.

In this study, CC grown on residual moisture from the cash crop and the large variability of climatic conditions between years caused large differences in the biomass production and N content. In accordance with Unger and Vigil (1998), the main constraint for cover cropping in semiarid regions is the availability of water at the time of sowing to ensure crop establishment. A good example was the 2007/08 season, even if there was residual water available in the soil profile the upper layers were dry and the CC growth was scarce since the roots unable to reach the residual moisture from deeper layers. If the benefits of CC are to be enhanced and homogenised between seasons, irrigation to ensure CC establishment is recommended. This will increase water demand in the cropping system. Based on rainfall observation of this study just a low irrigation (~20 mm) after sowing to ensure CC establishment could be enough.

Soil water content data combined with soil solutions from ceramic cups are a recognised indirect method for estimating NO_3^- leaching (Normand et al., 1997; Gehl et al., 2005), but the accuracy of water-percolation calculations below the root zone is one of the major limitations of the method (Arregui and Quemada, 2006). In this article, the agreement between drainage periods in the suction-cup and WAVE-simulated observations increased the reliability of the model simulation. The leaching losses occurred mainly in the NO_3^- form with the NH_4^+ being negligible and the NO_3^- concentration in the soil solution from the suction cups varying throughout the experiment. The barley treatment reduced drainage, leaching concentration and total amount of NO_3^- leached. In general, the barley NO_3^- concentration in the soil solution was lower than that of the other treatments because the N_{min} soil accumulation was also lower. The vetch and fallow treatments had a higher average NO_3^- concentration that peaked after periods of low drainage and soil N_{min} accumulation.

Barley greatly reduced the NO_3^- leaching throughout the experimental period relative to fallow. The main effect appeared during the intercrop period and in the years when the drainage was abundant. Only in the unusually dry autumn of 2007/08, in which the precipitation from October to March was 101 mm, were the drainage and NO_3^- leaching similar (nonexistent) for all of the treatments. This large variability is characteristic of Mediterranean semiarid regions, in which soil N_{min} accumulates during the dry intercrop periods and is leached out of the soil profile when an unusually heavy rainy season occurs (Ruiz-Ramos et al., 2011). At the beginning of the experiment, the N_{min} content just before sowing the CC was high (~300 kg N ha^{-1}) and similar for all the treatments; therefore, the CC had an opportunity to show their ability to reduce NO_3^- leaching. Both the barley and vetch cut the NO_3^- leaching losses by more than half relative to fallow. At the same time, the barley greatly reduced the N_{min} content in the soil profile, as it captured most of the available N, whereas the N_{min} content in the vetch soil was midway between those of the fallow and the barley owing to atmospheric N_2 fixation. After the 2007 maize cropping, all of the treatments converged to a similar soil N content, owing to the N mineralised from the cover-crop residues and the larger NO_3^- leaching (42 kg N ha^{-1}) in the fallow treatment. This trend continued throughout the experiment, and in the last year, the role of CC became evident. In the barley treatment, the N_{min} content in the soil profile and drainage were lower, so the NO_3^- leaching was greatly reduced relative to the other treatments. The vetch also decreased drainage owing to increased evapotranspiration, but as the soil N content was larger than in the other treatments, the reduction in NO_3^- leaching relative to fallow was less evident than for the barley. In general, the cover-crop treatments accumulated more N_{min} in the upper layers of the soil profile that control NO_3^- leaching, whereas in the fallow treatment, the NO_3^- leaching was larger and the soil N_{min} remained low after the intensive drainage periods. The effect of the CC in reducing the NO_3^- leaching during the intercrop period in the wet years was similar to that observed in more humid regions (Dinnes et al., 2002; Strock et al., 2004).

In dry years, when the soil NO_3^- accumulation during winter is appreciable, the CC play an enhanced role in controlling the NO_3^- leaching during the initial maize growth stages. During crop establishment, it is common to observe large NO_3^- leaching in irrigated areas, as water is applied in excess to ensure survival of the plantlets (Vázquez et al., 2005). In two years of our study, the barley reduced the NO_3^- leaching during the maize period relative to fallow. The reduction was a combination of lower N_{min} accumulation in the soil profile before the maize planting and lower drainage during the early growth stages. These results show that CC both control NO_3^- leaching and recycle N inside the cropping system, making them a potential biological tool to reduce N losses and N fertiliser application (Thorup-Kristensen et al., 2003).

5. Conclusions

The use of daily soil water-content measurements for an inverse calibration of the parameters of a physically based numerical model allowed quantification of the water balance components. Precipitation was the most important difference between the years, and evapotranspiration was the most important between the treatments. Evapotranspiration had a large sensitivity to LAI and K_c. CC that quickly developed their LAI in early autumn, led to an increase in evapotranspiration, a decrease in drainage and a reduction in NO_3^- leaching. The barley developed LAI and covered the ground faster than the vetch; therefore, it showed greater efficacy as a cover crop.

During the maize growing periods, the irrigation was adjusted to the crop requirements, and low drainage appeared only during the spring. The differences in drainage between the treatments during the maize period were derived from differences in the soil water content at the maize planting and were linked to water depletion by the CC.

The effect of the CC on the NO_3^- leaching was quantified by combining the NO_3^- concentration in the soil solution from suction cups with the water percolation below the root zone from modelling results. The concordance between the suction-cup observations and those of the numerical model increased the reliability of the simulations. The leaching losses occurred mainly in the form of NO_3^-, and the concentration in the soil solution varied throughout the experiment, depending on the rain and crop development.

In this irrigated maize system, the CC reduced the NO_3^- leaching and increased the soil mineral N in the upper layers. The main effect appeared during the intercrop period and in the years in which the drainage was abundant. For all of the treatments, leaching during the intermaize period represented more than 77% of the total NO_3^- leached during the study. In the dry years, when the soil NO_3^- accumulation during winter was appreciable, the role of the CC in controlling the NO_3^- leaching was also relevant during the initial maize growth stages. The barley was more efficient than the vetch at controlling the NO_3^- leaching, but the legume enhanced the N retention in the upper layers of the soil profile. The cover crops controlled the NO_3^- leaching and recycled the N inside the cropping system, allowing reduced N losses and N fertiliser application. Combination of field experimental results and modelling efforts allowed quantification of the main water and N balance components. This approach showed its capacity to analyse complex systems, particularly under highly variable climatic conditions.

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